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LOAN DOCUMENT

BIOLOGICALLY INSPIRED GUIDANCE FOR TACTICAL MUNITIONS

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Air Force Research Laboratory, Munitions Directorate

Abstract

Advances in new propulsion, materials, sensors, micro-electronics, and micro-manufacturing technologies offer the potential for constructing future low cost autonomous tactical munitions that, singly or cooperatively, exhibit behavior that approaches the complexity and flexibility of simple biological systems. Associated with achieving this potential is the requirement to perform complex computations in real-time that are far beyond even the projected capabilities of supercomputers running state-of-the-art mathematical computational algorithms. Challenges include context dependent processing of information from distributed networks of heterogeneous sensors, navigation and control in complex hostile environments, and guidance toward passively or actively deceptive objectives. These challenges are routinely met by living organisms using networks of neurosensory and neuro-effector circuits. With this motivation, this paper explores guidance concepts inspired by results from experimental insect biology.

Introduction

Advances in new propulsion, materials, sensors, microelectronics, and micro-manufacturing technologies offer the potential for constructing future low cost autonomous tactical munitions that, singly or cooperatively, exhibit behavior that approaches the complexity and flexibility of simple biological organisms. Associated with achieving this potential is the requirement to perform complex computations in real-time that are far beyond even the projected capabilities of supercomputers running state-of-the-art mathematical computational algorithms. Challenges include context dependent processing of information from distributed networks of heterogeneous sensors, navigation and guidance in complex hostile environments, and guidance and control during intercept of passively or actively deceptive targets. Living organisms, such as insects, using networks of neurosensory circuits, routinely meet these challenges. This paper explores guidance concepts inspired by results from experimental insect biology and neuroethology that will be applicable to future autonomous munitions and UAV (unmanned air vehicle) systems.

Tomorrow's battle space will be congested with information of varying qualities from various surveillance and information systems. Associated with this will be the problem of finding camouflaged, sparsely distributed mobile targets (e.g., theater missile TELS, mobile communication vehicles) in cluttered environments (e.g., urban back alleys, mountainous terrain, forests). Many of these scenarios will include large numbers of non-targets (e.g., friendly vehicles, buses, trucks), thus minimizing collateral damage will continue to be an important operational concern. In addition to camouflage and other passive defenses, it is reasonable to expect that high value targets will be actively defended and will actively employ various countermeasures.

Munitions operating in these conditions will require unprecedented capabilities to autonomously search for, detect, acquire, track, and engage their targets. Since large munitions cannot effectively operate in these kinds of scenarios, it is reasonable to expect that small munitions will have to be able to operate collectively to engage and destroy certain classes of targets. These munitions will have to navigate at relatively low speeds among obstacles and obstructions, while utilizing any relevant information regarding potential targets and rejecting non-targets and decoys. They will therefore require sensors and sensor fusion processing capabilities sufficient to provide large field-of-regard situational awareness. Stealthy operation to enhance munition survival may require inter-munition communication to be minimized for some scenarios.

There are many technology challenges that limit our ability to develop such munitions today. Probably chief among these is the development of hybrid

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distributed sensor information fusion and processing architectures suitable for low-cost small tactical air vehicles. Methods for design of flexible, adaptive, robust sensor networks to provide large field-of-regard situational awareness to autonomous air vehicles do not exist. Current autonomous target acquisition (ATA) and sensor fusion approaches are *ad hoc*, highly sensitive to various uncertainties, and impose large computational processing requirements. Contrast this with the fact that certain insects exhibit relatively complex behaviors with numerous heterogeneous sensors and relatively simple neural systems.

Operation in complex, cluttered, and uncertain environments requires the ability to design flexible, adaptive, robust guidance configurations that are beyond today's guidance and control theories and methods. Our current approaches rely on detailed knowledge of specific operational scenarios, captured implicitly in the mathematics of the methods or explicitly in the design models. Today's guided munitions are capable of high performance when employed under conditions for which they were designed (e.g., INS/GPS bombs in Kosovo, Tomahawks in the Gulf War). Finding and prosecuting TELS is a challenge with which we are still wrestling. Insects, however, are capable of finding food, finding mates, and avoiding predators in real-world conditions.

Social insects (e.g., ants, bees, wasps) typically search for food autonomously and exploit food resources collectively. This kind of behavior has the benefits of requiring minimal communication or centralized coordination. These strategies are good for finding and exploiting sparsely distributed, occasionally clustered resources in complex environments. They are precisely the kinds of strategies that should be explored for the engagements described above.

Our approach is to augment the guidance technologies that have proven so effective in recent conflicts, as well as new ones on the cutting edge of development, with concepts inspired by insect biology. Since we are munitions technologists and not professional biologists, we have initiated dialogues and cooperative research efforts with several of the premier insect neurobiologists and neuroethologists in the country. Several specific technology areas comprise the focus of our recent efforts to enhance munition capabilities. One area is the exploitation of sensor integration for small tactical munitions. We are beginning to explore development of integrated sensor/processing hardware for advanced seekers, navigation, and control systems based on insect neurosensory systems. One specific area of interest is to understand the mechanisms by which insects employ optical flow information for navigation, flight stabilization, and detecting targets against cluttered backgrounds. We are also exploring concepts for decentralized, hierarchical control based on understanding insect flight biology.

Tactical Munition Guidance

Future air-to-surface guided munitions will be designed for two classes of engagements: direct attack and wide area search. In direct attack, the target location is known *a priori*, given to the munition (e.g., in WGS-84 coordinates), and the munition flies from its known launch position to the designated target location using information from its on board inertial navigation system (INS).

The INS processes measurements from gyroscopes to give body rates and attitude, and accelerometers to provide acceleration, velocity, and incremental position. The information is used for both navigation and for augmenting the airframe flight stability. Fusing the information from these sensors provides kinematics information in 6 degrees of freedom relative to an inertial coordinate system (for short time of flight the earth's surface is adequately approximated to be an inertial system.). Typical technologies for the inertial sensors include ring laser gyros and, under development, MEMS based devices. A typical INS for air-to-surface applications would employ the HG-1700, which weighs about 1.2 lbs and exhibits performance typically specified by the gyro drift rate (about 1 deg/hr) and accelerometer bias (about 500 μg). In today's direct attack munitions, such as JDAM, GPS updates are utilized to recalibrate the INS in-flight. The INS and GPS solutions are fused, at varying levels of complexity depending on the specific concept, in a digital Kalman filter algorithm. The phase of the munition flight as the munition flies out without direct sight of the target is called *midcourse*, and the course correction steering function is called *navigation.*

If the target location is known only within some error, a direct attack munition requires a terminal seeker to achieve precise impact. Seeker technologies are being developed in several spectral regions and in both the active and passive modes. Spectral regions include "short wavelength" (UV, visible, near, mid and longwave IR), and "long wavelength" (MMW and RF). The short wavelength interest is motivated by the desire to provide high-resolution imagery for target identification and target track and aimpoint selection. The long wavelength interest (RF, MMW) is motivated by adverse weather penetration considerations. These

properties (implicit high resolution, and weather penetration) are essentially mutually exclusive for a single sensor mode due to competing physics phenomena. The most common passive seekers are visible and imaging infrared (IIR, typically 3. – 5. μm, or less commonly 8. - 10. μm). Recently, the emphasis has been on development of imaging seekers. Visible focal planes can be routinely obtained in 1024x1024 pixel arrays; MWIR focal planes can be typically 512x512, and 2 color passive IIR arrays are becoming available based on multiple quantum well technologies. For the guided munition application, the associated optics will provide an instantaneous field of view, or resolution, on the order of 0.5 milliradians.

Terminal guidance is traditionally considered to be taking place when the munition seeker has acquired the target, recognizes it as an acceptable target, and is providing guidance information to the munition guidance system to enable the munition to guide to the target. The INS and seeker output data are fused in the guidance software, typically consisting of relative state-vector estimator, guidance law, and autopilot modules. The relative state-vector estimator is usually some version of extended Kalman Filter, which incorporates seeker measurements with its internal mathematical model of the intercept to produce estimates of the target state relative to the munition. Based on this filtered seeker information, a terminal guidance law, typically a variant of proportional navigation, provides commands to the digital autopilot to steer the munition to intercept. The autopilot is an algorithm based on mathematical control theory that is designed to command fin deflections to provide active stability augmentation of the airframe, allowing the munition to fly with desired performance characteristics over a range of altitudes and velocities (its flight envelope). Current technologies for design of these guidance schemes build upon a rich body of mathematical control theory and experience with application of that theory. Achievable performance and robustness to uncertainties are constrained by limitations in the theory, in the processing throughput available, and probably in our imaginations. In fact, the performance of our designed systems tends to be heavily dependent on imperfect dynamics models, explicit or implicit in the guidance modules, and very sensitive to errors in those models. This sensitivity (in the control theory community *robustness* refers to low sensitivity to model uncertainty) is reflected in severe performance degradation in the presence of sensor noise, data latencies, and airframe aero-elastic dynamics, especially near boundaries of the designed flight envelope.

Wide area search munitions are a newly emerging class of munitions designed to attack mobile targets, the specific locations of which are unknown. The Powered Low-Cost Autonomous Attack System (PLOCAAS) project, an AFRL/MN Advanced Technology Demonstration program, is an example of this class of munition concepts. *Figure 1* illustrates a notional future operational concept for munitions of this class. Employing a variety of surveillance and information assets, enemy transporter-erector-launchers (TELs) are found to be operating in a relatively open area, though specific TEL numbers and positions are unknown. Groups of wide area search munitions are deployed in the area, as shown in the figure. The munitions use INS/GPS-based navigation to get into the target vicinity. As illustrated in *Figure 2*, each munition searches a designated part of the area using a scanning LADAR seeker. Each image, basically a detailed range map of the scanned scene, is processed with an autonomous target acquisition (ATA) algorithm to detect, acquire, identify, and track a TEL, while rejecting non-targets such as trees, buildings, or support vehicles. Finally, a munition that identifies a target guides to a close enough intercept to employ a multi-mode warhead against it. Since the warhead is relatively small, the munition must achieve a precisely timed attitude relative to the (possibly fleeing) target to effect a kill. The PLOCAAS guidance system represents the state-of-the-art in application of autonomous munition guidance systems for this kind of mission. The vehicle search and attack flight characteristics are tightly integrated with the seeker characteristics and the ATA algorithm processing sequence. Development of an ATA algorithm that has the required performance that will execute in real-time is cutting-edge technology. Furthermore, the munition represents a true guidance-integrated-fuzing (GIF) concept since the guidance seeker and ATA algorithm outputs are used for target aimpoint designation and warhead event timing. The design of such a tightly coupled guidance system presents a considerable challenge to missile designers.

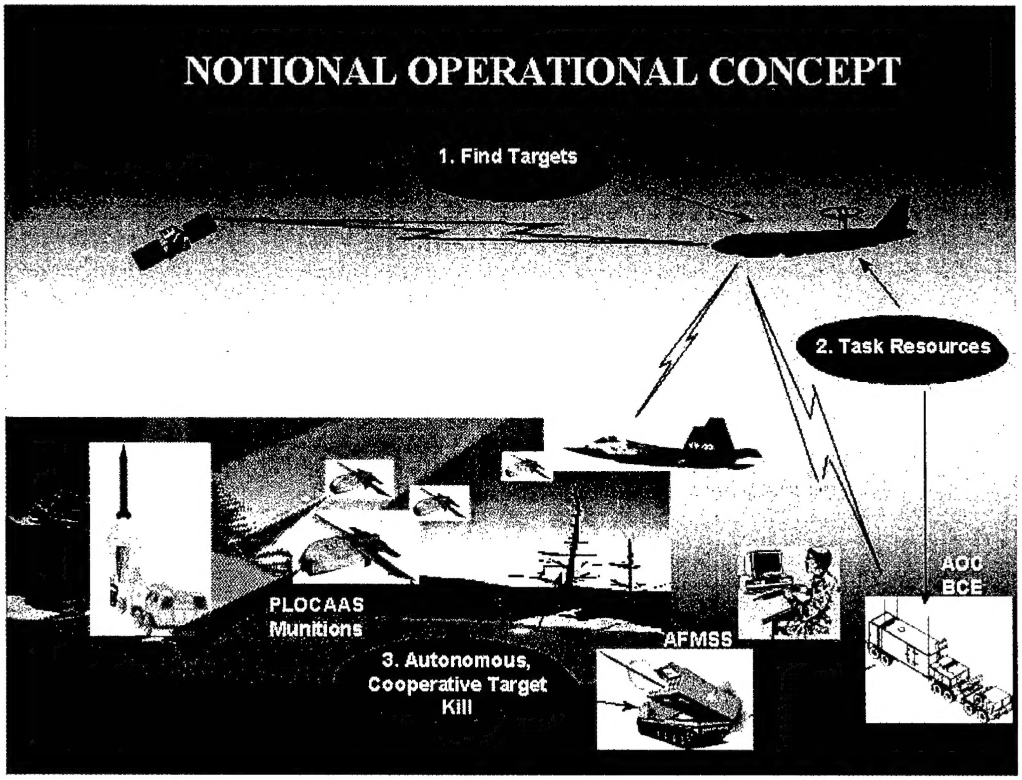

Figure 1

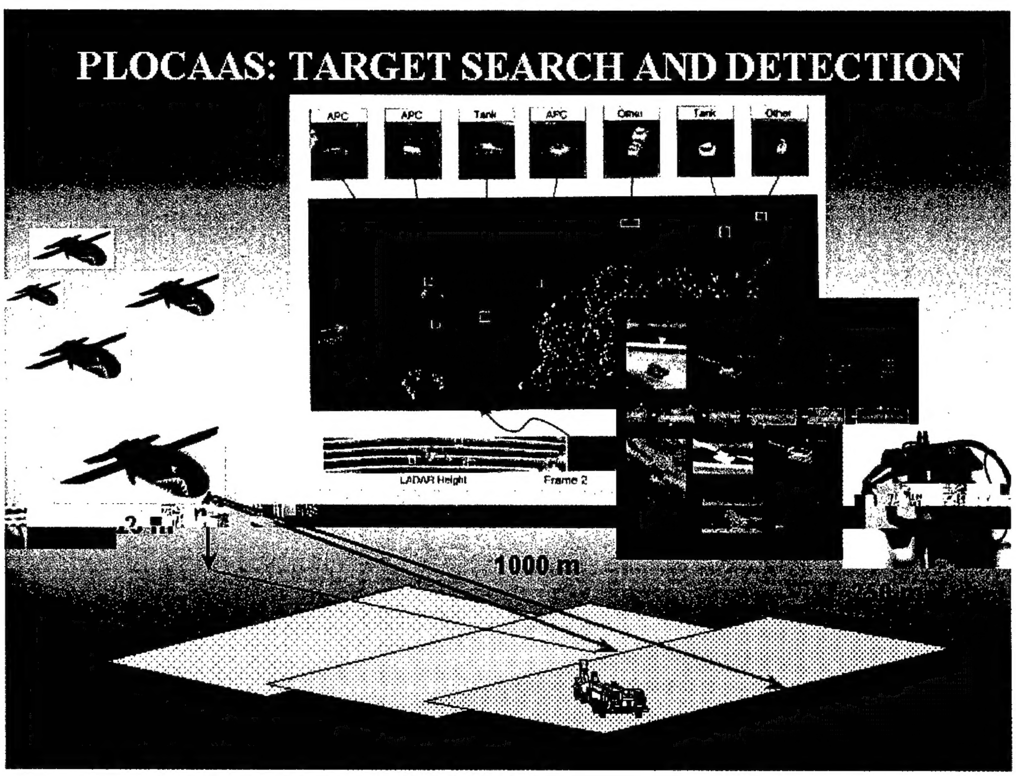

Figure 2

Insect Guidance and Flight Control

It should be obvious, even from this very brief discussion, that today's munitions rely on guidance systems that are based upon relatively few high-quality sensors, centralized digital data processing, model-based algorithm designs, high-speed digital microprocessors, and relatively tight tolerances on sensor, processing, and actuator subsystems. Development of future low cost munition systems for more and more challenging engagement environments exceeds the capabilities of current guidance system design concepts. To appreciate this, consider a not unreasonable extension of the wide area search munition operational scenario. Here, small autonomous air vehicles have the mission, individually or in cooperation with similar vehicles, to search for, acquire, identify, track, and intercept deceptive targets in an cluttered imperfectly known environment. The particular scenario could be a group of tactical munitions on a mission to destroy missile launchers that are operating in the back alleys of an urban area, or rescue UAVs searching for a downed aircraft in hilly, tree covered countryside. The air vehicles utilize some combination of on-board sensors and communication to seek out and intercept their actual targets in information rich environments that include other air vehicles, stationary and moving objects to be avoided, and potential targets.

While these kinds of operational capabilities are still in the realm of science fiction for man-made systems, they are precisely the kinds of capabilities exhibited by flying insects (e.g., houseflies, dragonflies, butterflies) in their day-to-day activities. As depicted in *Figure 3*[*], flying insects possess a complex visual system of faceted compound eyes and massively parallel visual processing. The insect retina converts light into electro-chemical neuronal activity. The information is processed in a sequence of neuronal structures (lamina, medulla, lobula, and lobula plate) that comprise the insect forebrain. Insect eyes typically are of very low resolution but are very sensitive to motion. This motion sensitivity comes from processing of wide-field motion (optical flow) and small-field motion (e.g., objects moving against a cluttered background) in different neurons in the lobula complex. The neuronal architecture is such that the structural information content of the 2D image on the retina is largely preserved (i.e., the visual processing architecture is retinotopically mapped). The visual information is then combined with information from a variety of other sensors and utilized for flight. As illustrated in *Figure 4*[†], dipterous insects (e.g., houseflies, fruitflies, horseflies) have modified hind wings, the halteres, which detect body rotation rates by sensing Coriolis forces. Additionally, insects have strain sensors distributed about the body and wings (campaniform sensilla), olfactory and air flow sensors on the antennae, and head-body orientation sensors on the thorax. Some of this sensory information is processed with information from the visual system and utilized locally, while other sensory information is centrally processed and used globally.

[*] Images adapted from Franceschini[11] and Strausfeld[21].

[†] Images adapted from Dickinson[6] and Chapman[5].

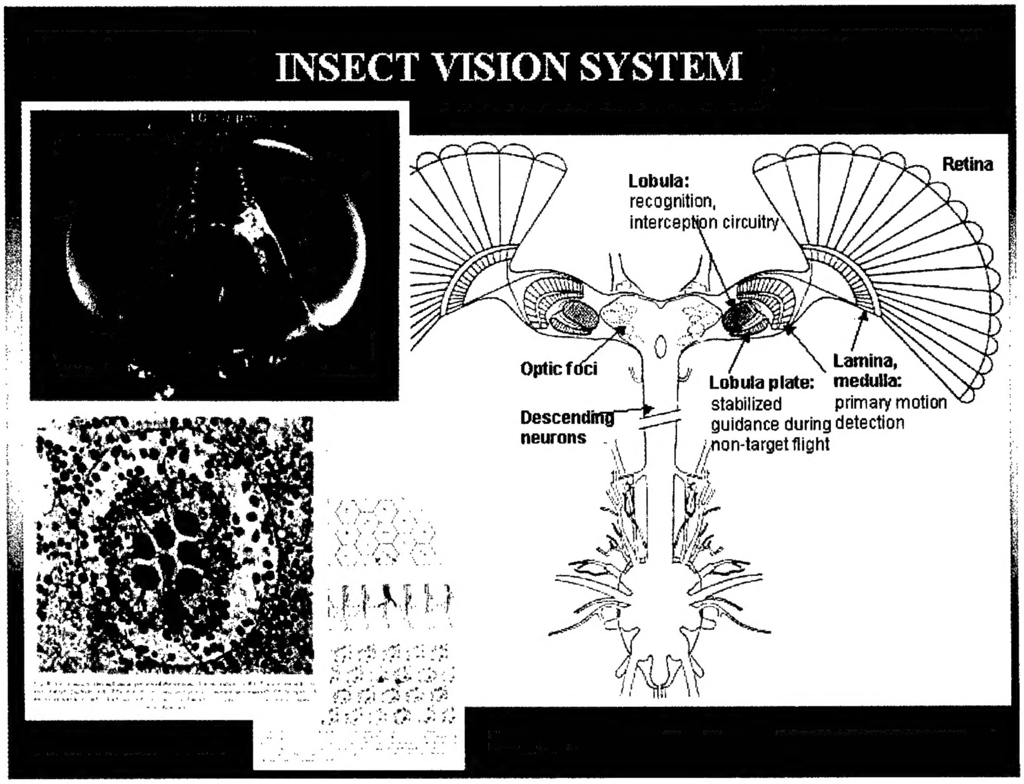

Figure 3

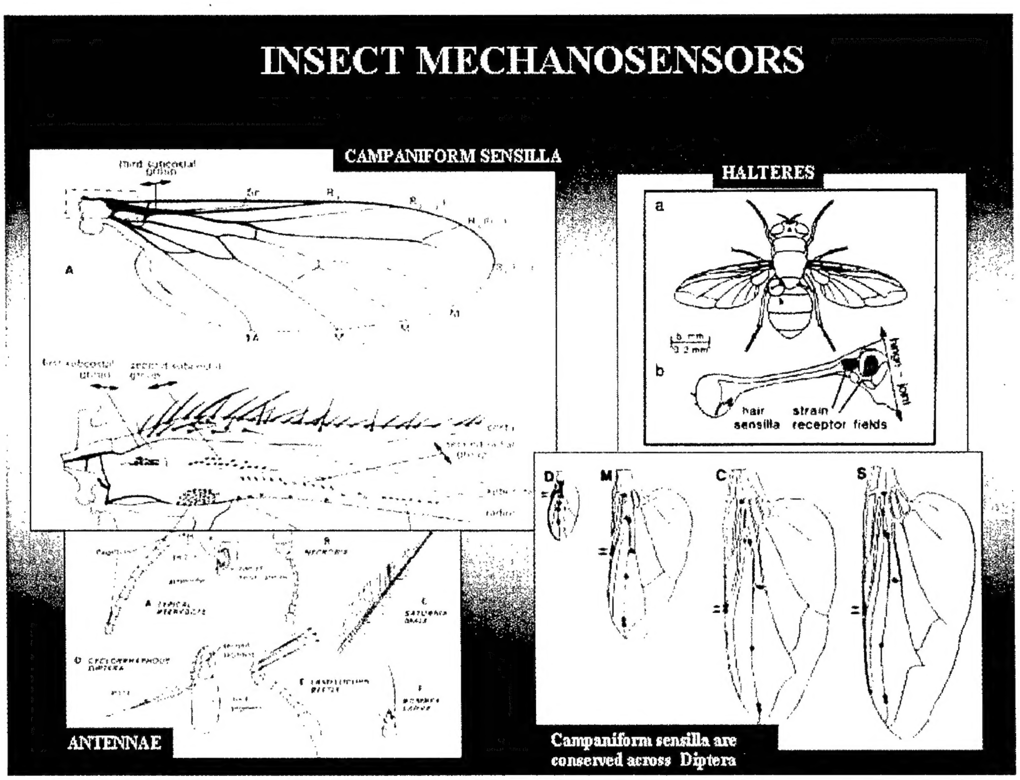

Figure 4

Because munitions and insects exist in such different flight regimes it is probably not very productive to try to quantitatively compare their sensory and flight capabilities. Several qualitative observations are worth making, however. Both munitions and insects are capable of extremely precise flight, in their respective nominal flight regimes. We expend a great amount of effort to design munitions that meet specified performance criteria. We then expend a great amount of effort verifying, in digital simulation, hardware-in-the-loop simulation, and flight tests, that in fact they meet those specified criteria. Unfortunately, with the world's rapidly advancing technologies, the length of time during which those criteria yield performance superior to that of our adversaries' capabilities is growing ever shorter. Hence, the tendency for Preplanned Product Improvement programs to be initiated even before initial production is well underway for many of our weapons systems. Guidance technologies that yield flexible, adaptable munition systems would revolutionize weapon development. Insect biologists have long noted the adaptability, flexibility, and robustness of various insect flight control systems. They believe, and we concur that their evidence supports, that the source of these characteristics lies in the architecture of the sensors, processing, and effector configurations associated with flight. Add to this the observation that insects have far more complex autonomous flight behavior than today's munitions. These behaviors include landing, hovering, and flexibility and robustness of their flight capabilities in very cluttered, complex, and hostile environments. This latter characteristic, in particular, contrasts with the state-of-the-art in munition guidance systems.

Munitions and insects obviously represent very different guidance system "design strategies". Munition guidance systems represent highly tuned, relatively high performance and expensive sensor, processing, and actuator configurations that rely heavily on detailed modeling, analysis, and centralized processing to realize predictable performance under anticipated conditions. Insect guidance systems seem to represent more coarsely tuned, relatively lower component quality distributed sensor, processing, and actuator configurations that exhibit system-level robust performance even under extreme conditions. We believe that the strengths of each design strategy address, to some degree, the weaknesses of the other. Thus, our approach is to begin with a foundation in state-of-the-art guidance component technologies (sensors, processing, algorithms, actuators). With the help of insect biologists, control theorists, mathematicians, and aerodynamicists we are exploring ways of building system configurations that have some of the functional performance characteristics of insect flight behavior, while retaining the desirable engineering characteristics of highly tuned munition systems.

As we push the limits of today's guidance system technologies, we are also exceeding our capabilities of accurately predicting free flight performance. Thus, we need to develop new conceptual frameworks for analysis of guided vehicles with increasing levels of autonomy. Understanding at some fundamental level the various ways insects do these tasks, and particularly the mechanisms by which they achieve incredibly robust flight behavior, should help us break out of the rigid thinking constrained by available hardware, and develop fundamentally new ideas of how to perform the necessary navigation and guidance functions for autonomous guided munitions.

Insect Biology-Inspired G&C for Munitions

Optical flow is the apparent motion of brightness patterns across an image plane induced by a vision system moving relative to objects or background being imaged. The motion field related to optical flow may be illustrated by a field of vectors on an image plane, the magnitudes and directions of which represent instantaneous relative velocities in the image segment induced by translational and rotational body motion. Although the motion field and optical flow are related, they are not identical; shadows, for example, may induce changes in brightness that produce optical flow, even in the absence of motion. The motion field represents perceived relative motion and may be due to actual motion of the observer, to motion of the objects or background relative to the observer, or to some combination of the two. Optical flow induced by rotational body motion is invariant to range of the object field from the sensor. Translational motion induced optical flow depends on relative ranges of the objects from the sensor: distant objects appear to move at lower relative velocities than close objects for the same sensor velocity. Refer to Horn[13] and Verri[22] for discussions.

Insects utilize optical flow for navigation, detecting and tracking prey or mates in flight, obstacle avoidance, landing, and flight stabilization. Similarly, optical flow processing has obvious use in munition guidance systems for target detection and tracking in cluttered backgrounds. Optical flow information has been considered for augmenting munition INS/GPS navigation systems; this would be useful in environments where the GPS signal is jammed or otherwise degraded. The question of developing munition guidance systems that use optical flow for obstacle avoidance, landing (or, in

the case of munitions, achieving tight relative attitude control for warhead pointing at intercept), and flight stabilization is still open. At first glance, considering the relatively high quality of INS angular and translational velocity estimates, it may seem questionable to consider the usefulness of another source of this information for flight stabilization. Also, unlike INS gyros and accelerometers, optical flow data do not unambiguously resolve rotation and translational motion without additional information. There are, however, at least two reasons for investigating this possibility. For strapdown sensor applications (e.g., flash LADAR), another set of independent body measurements may allow some degree of decoupling of the seeker track loop response from the guidance loop response, a source of guidance error in these systems. For the autopilot designer, it may be possible to reduce the impact of body flexible dynamics on the control system response since, due to size considerations, the INS and seeker are not typically collocated on the airframe.

Various classes of optical flow processing algorithms have been developed for image processing and robotics navigation applications (e.g., differential, region-based, frequency-based, and phase-based methods; see Barron[2] for a discussion). Although details of the algorithms are not particularly relevant to the context of this paper, good discussions and limited comparisons of some of these techniques are available in Barron[2], Kumar[16], Srinivasan[20], and their references. Strausfeld[21], Krapp[14,15], Egelhaaf[10], Borst[4], Hausen[12], Bialek[3], Douglass[8], and their references contain good descriptions of insect visual systems and concepts of matched filters representing insect optical flow processing. The argument for investigating insect processing of optical flow lies less with the benefits of making comparisons among the particular algorithms insects use and various mathematical approaches, than with the potential benefits of exploring real flight control systems built around the use of optical flow processing. An analogy with state estimation in guidance loops will serve to make the point. Kalman filters used for target tracking in open loop conditions (e.g., ground stations tracking aircraft or satellites overhead) typically are tuned differently than state estimators in missile homing guidance loops. In closed loop guidance, the filter's dynamical properties (e.g., low-pass with a given time constant) impact the guidance performance at least as much as, if not more than, the quality of its estimates as the missile nears intercept. It is reasonable, therefore, to expect to learn something useful from understanding the mechanisms of insect optical flow based closed-loop flight control.

Micro-electromechanical sensors (MEMS) and actuators devices are being developed and are of increasing interest to DoD since they are small, light weight, presumably reliable, and inexpensive. The oldest MEMS applications are micromechanical IMUs, under development by several "aerospace" firms. (A MEMS IMU could be collocated with the seeker, further reducing impact of body flexible dynamics on control system response.) MEMS sensors (such as pressure sensors) and effectors (such as miniature air flow control devices) are being developed in various Air Force and DARPA projects. A particularly appealing idea is use of fields of MEMS sensors and actuators for active flow control in propulsion or aerodynamic flight control applications (e.g., to augment traditional aerodynamic surfaces). The idea is to use the devices to interact with unsteady aerodynamic flow, producing large control forces for small actuation forces (for discussions see Roos[18], Amitay[1], Smith[19], Rathnasingham[17], and their references). The touted benefits include enhanced aerodynamic efficiency, increased maneuverability, reduced control surfaces, and post-stall controllability, among others. There are many technology challenges; not least in designing configurations for control of highly nonlinear, imperfectly modeled flows using distributed local sensors and actuators. In fact, no generally applicable mathematical model-based controller design methodologies exist for such classes of problems.

As Dickinson[7] and colleagues have effectively shown, flies use unsteady lift mechanisms for a substantial portion (e.g., >35%) of the lift forces they generate during flapping flight. They control production of these forces with elegant hierarchical control systems that include numerous sensors (again, refer to *Figure 4*) and relatively few actuators (e.g., large asynchronous power muscles and small synchronous steering muscles). It would certainly be a stretch of reason to equate flapping flight with use of MEMS devices for fixed wing or rotorcraft flight. Still, the fact that insects demonstrate that precise flight utilizing unsteady aerodynamics can be accomplished using coarse sensors and largely analog processing (e.g., the neuronal networks), and without reliance on detailed mathematical models (whether predicted from CFD computations in real-time or obtained empirically from exhaustive wind-tunnel testing) is of interest. Again, the particular mechanisms of their flight control configurations may be of less use to the munition designer than understanding the "design guidelines" by which their sensor-effector control loops are arrayed. Refer to Dudley[9] for a detailed discussion of insect flight mechanics.

A Biological Perspective

The paper began with a brief discussion of some guidance technology challenges confronting the designer of low cost autonomous munitions that will have to operate in the highly uncertain battlefield scenarios of the future. These technology challenges arise from the requirement for cost effective operational performance capabilities that are generally lacking in today's tactical munitions and that appear to be beyond the reach of conventional guidance system design approaches. We made a case for exploring analogs of these desirable capabilities in the behavior and neurobiology of flying insects. We would like to conclude this paper with a few additional comments about our perspective for exploiting insect biology for munitions guidance systems.

Insects possess a vision system with features that offer potential for improving weapon performance. We want to capture some of that *functionality* in designing seekers that accomplish much of the image and signal processing in hardware (e.g., hybrid analog/digital VLSI circuits) rather than software executed on a digital microprocessor.

Insects are capable of precise flight (e.g., dragonflies, hoverflies). Since we are not considering development of flapping wing munitions, we want to find ideas for new control configurations, inspired by insect flight neurobiology, that will apply to future conventional air vehicle flight (e.g., exploit the potential of MEMS devices for active flow control).

Insect neurosensory systems process information from large numbers of sensors under widely changing environmental conditions. These networks of sensors, neurons, and effectors exhibit an information processing capability that is vastly more robust and flexible than the systems we know how to design for munitions. Even given the inherently slow signal propagating speeds of neurons (at least when compared with electronics), the information processing speeds of insect neurosensory networks are still fast enough for insects to exhibit flight behavior that is quite astounding when compared with that of current manmade autonomous air vehicles.

Not all features of an insect's neurosensory systems are the result of some optimizing process. Some are merely by-products of the process of adapting existing structures to new functions (e.g., human appendix, small toe, 90% of the brain cells we don't use). Thus, as a general philosophy we want to look to biology for *inspiration*, not for engineering templates.

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18 SEP 2000

1ST Ind to AFRL/MNG Ltr, 14 Sep 00, Request for Review and Clearance

AFRL/MN CA-N

TO: AAC/PA

Recommend approval for public release of the paper entitled "Biologically Inspired Guidance for Tactical Munitions," to be presented at the AIAA Missile Sciences Conference in Monterey CA in Nov 2000..

Frederick Davis

FREDERICK DAVIS
Acting Chief Scientist
Munitions Directorate

Attachments: n/c

2nd Ind, AAC/PA

26 September 2000

TO: AFRL/MN CA-N

Approved.

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DEPARTMENT OF THE AIR FORCE
AIR FORCE RESEARCH LABORATORY (AFMC)
EGLIN AIR FORCE BASE, FLORIDA

14 SEP 2000

MEMORANDUM FOR AFRL/CA-N

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SUBJECT: Request for Review and Clearance

1. Request review and approval of the attached technical paper. Pertinent information is as follows:

Title: "Biologically Inspired Guidance for Tactical Munitions"
Author(s): Evers, Johnny H. and Wehling, Martin F.; AFRL/MNG
Submission: AIAA Missile Sciences Conference; Monterrey, CA; Nov 2000.
Sponsor: AIAA
Distribution and Classification of Proceedings: Unclassified, DTIC. Paper will be marked for Distribution Statement A, Unlimited Distribution.
Submission Date: 15 Sep 2000
No Foreign Nationals will be in attendance.

2. The material contained in the attached paper is technically accurate, unclassified, and suitable for public release.

3. Even though key words that appear on the Militarily Critical Technologies List (MCTL) are included in the paper, the particular aspect of technology which this presentation addresses is not included as part of the MCTL and will not result in the transfer of any militarily critical technology.

4. Figures 1 and 2 on page 4 were adapted from a LOCAAS presentation that was approved for public release in March 1999.

5. Please contact Mr. Johnny Evers, AFRL/MNGN, 882-2220, ext. 3330, if you have any questions.

Sandra M. Lefstad
SANDRA M. LEFSTAD
Chief, Advanced Guidance Division

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Conference paper